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Crafting the Digital: Developing expression and materiality within digital design and manufacture

David Grimshaw[a*]

[a]Manchester School of Art
[a]Manchester Metropolitan University
*Corresponding author e-mail: d.grimshaw@mmu.ac.uk

Abstract: The paper presents practice led research that seeks to challenge current approaches to 3D digital design and manufacturing, and its application in the production of highly regulated, controlled and predetermined outcomes. Inspired by the works and writings of David Pye (1968), the paper presents a practical investigation into the production of digitally designed and manufactured wooden vessels. The research develops approaches to manufacture where the final physical characteristics are not fully determined within the CAD modelling phase, and applies craft making knowledge within the digital machining processes to develop expressive forms and surfaces that are responsive to the physicality of making, and the material of manufacture.

Keywords: craft, digital, routing, materiality, expression

1. Introduction

The research seeks to challenge 3D digital design and manufacturing, and its application in the production of highly regulated, controlled and predetermined outcomes. The use of digital technologies within design and manufacturing has enabled the development of high levels of precision within the design development, CAD modelling and digitally controlled production of work. “ThomasNet” America’s leading on-line product engineering procurement site, promotes the benefits of digital manufacturing thus:

“There are many advantages to using CNC Machining. The process is more precise than manual machining, and can be repeated in exactly the same manner over and over again. Because of the precision possible with CNC Machining, this process can produce complex shapes that would be almost impossible to achieve with manual machining. CNC Machining is used in the production of many complex three-dimensional shapes. It is because of these qualities that CNC Machining is used in jobs that need a high level of precision or very repetitive tasks.” (Thomasnet.com)

However, I believe that the development of the design process from the physical to the digital has had some undesirable consequences and the current emphasis on developing design work using screen based CAD is detaching designers from the physical experience of material making. This is especially evident within design education with its emphasis on the acquisition of CAD skills, and where banks of computers are replacing physical workshops. Chief Design Officer for Apple, Jonathan Ive, highlighted this issue in discussion with Deyan Sudjic, director of the London Design Museum: (Winston, 2014)

"So many of the designers that we interview don't know how to make stuff, because workshops in design schools are expensive and computers are cheaper…That's just tragic, that you can spend four years of your life studying the design of three dimensional objects and not make one"

Ive went on to observe:

"You can't disconnect material from the form… sometimes you see car interior sketches, where, obviously there's form and there's divisions of forms and some lovely colouring in – those boys can do a really good colouring in – and then there are these arbitrary bits of wood. And you think, wood's not that shape. Of course we can make anything any shape, but that's just being bloody minded. You can't make those decisions, you can't read about it, you gain that experience by making."

The detachment from making within contemporary design for manufacturing is not developing the haptic and tacit knowledge within designers that are the traditions of craft and material making and can inform further material opportunities within the digital design development process. However, there are areas within digital manufacturing where opportunities for more expressive and materially responsive approaches can be more readily utilised. Whilst there are aspects of production and manufacturing where uniformity and standardisation is the aim, such as design and manufacture of cars as highlighted by Ive, there are other areas with a reduced need for high levels of tolerance and regulation, where consistency and repeatability is less essential within the final outcome. One such area of digital manufacture is the use of the CNC router for the milling and carving of solid timber, and this is the focus of my research.

The CNC router is a tool located at the convergence of processes that can be understood to be at once manual, mechanical and digital. The machine has the flexibility to enable the introduction of physical variations within the digital manufacturing process, adjusting the output through variation of cutting tools, and the resolution of surface finish through adjustments to stepover distances.[1]

The use of wood within this digital making process is also important, as a natural material it has variation and character that can inform the design and making process in a way that a homogenous and physically consistent man-made raw material cannot.

The use of wood also connects digital manufacturing with the craft traditions of material hand making, and is reflective and responsive to the discourse around making and manufacturing proposed by David Pye (1968) within his definitions of workmanship. Pye proposed definitions of making practice as the "workmanship of risk" where a maker's skill and judgement are causal to the individuality of making, and the "workmanship of certainty" where an object's manufacture is highly regulated and predetermined.

[1] "Stepover" is the distance between each cut when milling with a CNC router.

Whilst pre-digital, Pye's own work usefully interrogated the interrelationship of maker, material and machine/technology, utilising a self-made 'Fluting Engine' (figure 1) which allowed for manual

Figure 1: Fluting Engine (Pye, D. (1986), Wood Carver and Turner, Crafts Council (p47))

control of a chisel held within a movable frame to control the direction, depth and arc of the cutter.

The engine produced radial cuts to carve out hollow vessel forms, but allowed for variations to the:

- radius and angle of the cutter
- relationship of the cutting path to the centre of rotation of the block
- size and angle of the block being carved
- block to rotate in either a circular or elliptical path

From these limited variations to the physical cutting process, a wide variety of beautiful and subtly

Figure 2: Dishes W14 & W8 (Pye, D. (1976) Retrieved November 2016 from http://collections.craftscouncil.org.uk)
Images: Todd-White Art Photography

detailed forms and surfaces could be produced (figure 2)

Through Pye's use of his 'Fluting Engine', the level of skilled hand making was semi-automated, and to a great extent the "workmanship of risk" reduced. Pye's repetitive, mathematical and semi-mechanised process was in many ways predictive of contemporary CNC router manufacturing, which was developing towards the end of his career – and this relationship was not lost on Pye, stating:

> "…I'd be fascinated to see the sort of things I make being turned out by a computer – I really would – I'd love to see it. I bet I could do it better than the computer all the same!" (Frayling, 2011 (p108))

There are of course examples of current craft practitioners using CNC Routing to produce beautiful wooden forms, such as "Ves-el" (figure 3) by Gareth Neal in collaboration with Zaha Hadid. "Ves-el", commissioned for "The Wish List" exhibition[2], used a combination of complex CAD modelling, technically challenging CNC routing, and highly skilled crafts making to produce an impressive piece of digital craft making.

Figure 3: "Ves-el" (Neal, G. & Hadid, Z. (2014). Retrieved November 2016 from www.garethneal.co.uk/the-wish-list)

Neal described how he was *"interested in the idiosyncrasies of traditional hand process such as a hand-thrown pot or a raised piece of silverware, and how simulating these could be achieved through digital imitation"*. (Slavid, 2014)

Whilst the project recognises and references the value that hand-making brings to physical characteristics of form and surface within other areas of craft making, for me "Ves-el" feels overly dominated and pre-determined by Hadid's CAD modelling process, as opposed to Neal's craft making and material knowledge.

There appears to have been a missed opportunity within the collaboration to develop the form and surface character through a more empathetic integration of the physical making process, as informed by Neal's craft knowledge. As such "Ves-el" lacks the making efficiency that is evident in Pye's work, where the development of surface and form character is directly informed by his craft knowledge of the physical tool within the process of material making.

This opportunity to more fully integrate digital and craft knowledge within a digital craft and design process, is the area where my own research is focussed, investigating the use of CAD/CAM design

[2] "The Wish List" was a series of collaborative projects that paired established design leaders, with emerging designers and makers. The results were exhibited at the V&A Museum, London, in September 2014.

and manufacture where the design development and material making are not dominated, or pre-determined, by the CAD modelling process. There is an opportunity to embed craft approaches and material and process knowledge within digital design and manufacturing, to enable the character of form and surface to continue to be developed after the CAD modelling stage, exploring the characteristics revealed by empathetic interrogation of the physical making process of the CNC router.

2. Previous bowl making on the CNC Router

This research is not my first work using the CNC router, figure 4 illustrates the bowl cutting process and sequence I have utilised in earlier making, using a comparatively basic 2.5 axis CNC router[3]. It is important to be aware of the sequence necessary for cutting complex work such as a wooden bowl on a CNC router, which is not a simple act of pressing a button and a bowl is made automatically. It is not a fully automated process and has a complexity in the making sequence that might not be evident to practitioners used to using more fully automated digital manufacturing processes such as 3D printing.

Figure 4: previous bowl cutting on 2.5axis CNC router

The wood to be cut is screwed into a spoil board[4] from underneath. Positioning of the screws is important as they must not clash with the path of the cutter during machining, thus damaging the tool. The holes left by the screws are also best positioned in areas that are not visible on the finished piece, or better still in sections that can be easily removed at the end of the cutting process. For this piece the screws were positioned at the end of the lugs (or handles), which were made overly long in order for the material containing the screw holes to be removed on completion of machining.

The inside of the bowl is first rough-cut, then fine-cut. The top surface of the work is not machined, to enable a flat surface to be maintained. When the work is inverted and re-fixed onto the spoil-board for the external cut, this flat surface allows for safe and secure mounting in preparation for the cutting of the outer surface.

[3] 2.5 axis CNC router can cut/move in the three X,Y & Z places, but only cut in 2 planes at any one time, i.e. X&Y, X&Z or Y&Z
[4] The "spoil board" is the board on which the work is mounted on top of the bed of the CNC router. It can be cut into (or spoiled) as part of the manufacturing process, to be discarded after cutting

It is also important when inverting the work that an accurate datum is maintained to ensure a precise correlation of internal and external cuts, as the external routing is cut blind, without view of the previous internal cuts. After roughing and finishing the outer surface, the work is demounted, and the ends of the lugs (where the fixing screws were positioned) are removed to produce a clean finish to the final piece.

This work also followed the more traditional method of tool selection, with the roughing out using a square-ended cutter, and finishing with a round-ended cutter. The usual aim for the finishing cut is to leave as smooth a surface as possible, with minimal scalloping left by the round-ended shape of the tool. The standard formula for setting the stepover for the finishing cut is to set a distance of between 1/5th - 1/10th the diameter of the finishing tool (i.e. 3mm round end finishing tool = 0.6mm - 0.3mm stepover) (GRZsoftware.com).

This formula is derived from the fact that the middle 1/10th section of a round-ended finishing cutter is close to flat, thus minimising the scalloping effect of parallel cuts (figure 5). By taking multiple small stepovers, the resultant surface will also more closely replicate the CAD model, although for a large piece of work 1/10th stepovers can take significant time to complete. To increase manufacturing speed and cost efficiencies, a stepover of up to 1/5th might be used, but this will result in more pronounced scalloping to the material surface. If the ambition is to achieve a smooth finish that more accurately reflects the CAD model, a high level of scalloping on the finished surface would be

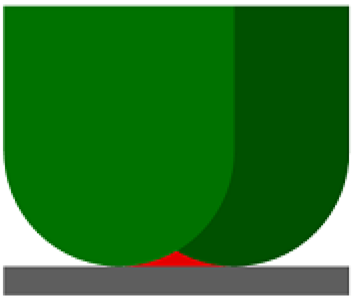
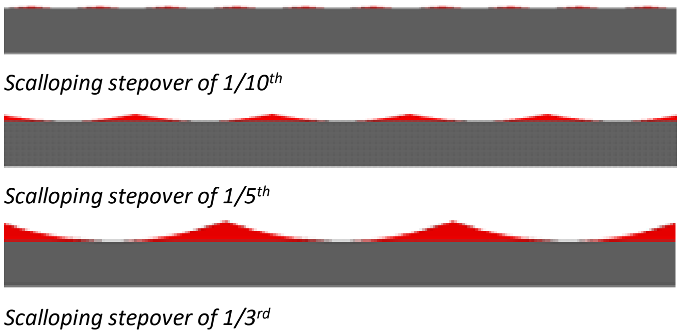


Figure 5: Scalloping caused by adjacent passes of round-ended cutter – shown in red



deemed undesirable.

(GRZ software, (n.d.) Retrieved November 2016 from http://www.grzsoftware.com/blog/how-to/choose-stepover)

It is also necessary to consider the complexity of the surface geometry when choosing cutter sizes and stepover distances. The more complex the geometry, the finer the finishing tool that is needed, and subsequently a smaller stepover distance is set. However, to minimise scalloping within complex geometries and optimise cutting efficiency, one should aim to use the largest diameter tool that the geometry allows (GRZsoftware.com).

The resultant work (figure 6) is highly accurate, reproducing the detail of the CAD model to such an extent that the facets on the model can be seen on the surface of the wood. However, the cutting tool and the process of CNC Routing are almost completely removed from the character of the work, and as such the finished form and surface is almost entirely a result of the CAD modelling process.

On reflection of this highly regulated making process, I realised that the point where the work embodied the most interesting relationship between the CAD modelling and the physical making process was after the rough cut, but before the finishing cut. The rougher surface at this stage had a textural quality more akin to hand wood carving, and was more materially engaging than the smooth

Figure 6: Homage to David Pye – CNC Milled Bowl – David Grimshaw 2014

finished surface.

This observation led me to reflect further on the work of David Pye, Gareth Neal and Zaha Hadid. My conclusion was to seek to develop a more materially engaged and sensitive response to the physical making process of the CNC router. Instead of the highly regulated and predetermined approach of the engineer, I would use the technology to seek expression of form and surface, as would a sculptor or artisan wood carver.

3. Research Methodology

The research methodology set out to test systematically the effect that changes to only the physical set-up of a CNC router would have on altering the output produced from a simple common CAD modelled form. The common model would be re-manufactured with iterative changes to cutter size and stepover, to test the effects of these changes, and enable the differences in the outputs to be directly compared.

4. Research Exploration

4.1 Internal bowl cutting

My investigations continued on the 2.5 axis CNC router, and a simple common CAD form of three intersecting spherical bowls was developed (figure 7).

Having three separate bowls within the common model enabled the stepover of the

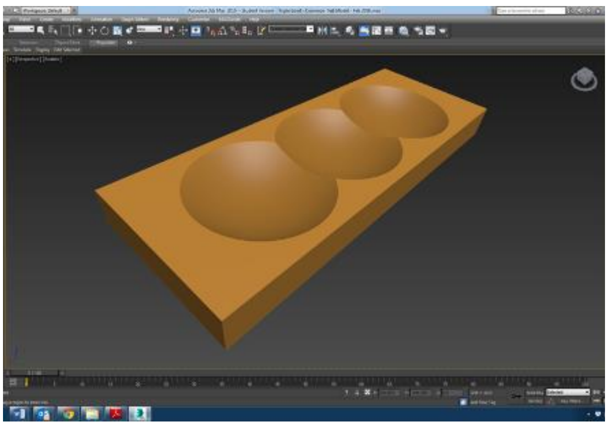


Figure 7: common triple bowl CAD model

finishing cut to be individually set for each bowl. This resulted in the different surface textures for each cut, and the effect of these changes on the intersection between the bowls, to be observed.

It should be noted that the common CAD model has a smooth finish to the interior surface of the bowls, and as such all textural surface variance is due to the set-up of the CNC router and the physical cutting of the work, and not a result of variations within the CAD model.

For these tests, maple was selected as the material as it has a clean, consistent but minimal grain pattern, ensuring that changes observed were due to the changes in cutting, and not to differences in grain character between samples. As the finishing cut was to be relatively deep in comparison to the usual fine finishing cut, the work was orientated so that the final cut was along the grain, to reduce tearing and produce a clean cut.

Figure 8: common model using a 10mm cutter Stepovers set at 7mm, 5.5mm, 3mm step overs

Figure 8 illustrates the result of using a 10mm round end cutter, with a stepover variance of 7mm, 5.5mm and 3mm.

The size of stepover, and the resultant heavily scalloped surface, affected the grain character considerably over the surface. The smaller the stepover, the shallower the cut and the more the grain pattern appears to flow across the grooves, and across the whole surface.

As expected, the larger stepover resulted in a more pronounced scalloping to the surface finish. However, what wasn't expected was that the deeper the scallop, the more the resultant grain pattern sat within each individual groove, resulting in a more fractured grain pattern to the finished surface. By contrast, the smaller stepover resulted in a shallower scallop, and the grain pattern appears to flow across the whole surface of the work (figure 9).

The effect of the differing scallop sizes on the grain pattern was to visually distort the grain, as if

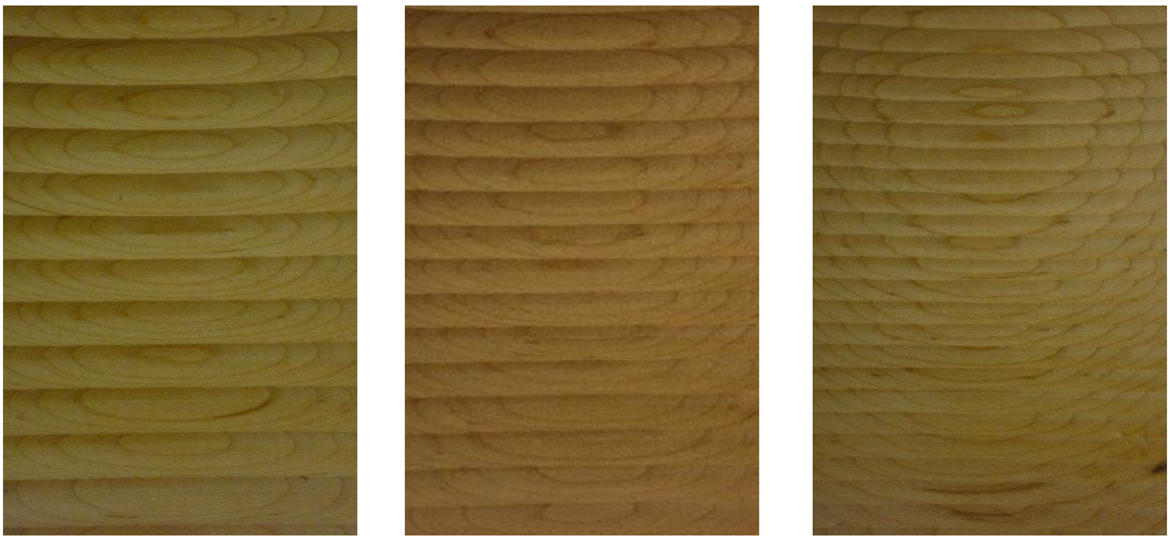


Figure 9:
7mm stepover detail *5.5mm stepover detail* *3mm stepover detail*

viewing the surface through reeded glass[5] or moving water, as if diffracting the grain into ripples.

This unexpected effect highlighted the importance of practice-based material testing. It enables a close observation of the physical results of making, which is especially important in discerning results that are unanticipated but characterful. It is the exploitation of these effects that is central to the development of the more expressive and materially engaging forms and surfaces, which is the central tenet of the research.

Subsequent tests with 8mm and 6mm cutters highlighted a consistency of results when differing stepovers in proportion to the size of the cutter, developing similar variation across the results. However, with each reduction in cutter size and stepover, the effect on the grain was less pronounced due to the grain size remaining constant in the material, so the smaller the cutter and stepover size, the lesser the effect of visual distortion. To maximise the observed visual effects, the size of cutter and stepover needs to be proportional to the size of the grain character of the timber, and the size of the work being cut. The finer the grain, and the smaller the work, the smaller the cutter and the stepover.

4.2 External bowl cutting

Further tests investigated the effect of cutter size and stepover on external cuts. From the results gathered from internal tests, a 10mm cutter was selected to maximise the visual effect of the grain, and the physical texture to the scalloping of the surface.

A CAD model of multiple intersecting bowls was developed, to observe the scalloping effect on the outer surface, and the detail of the intersection from one form to the next, with stepover set at 6mm

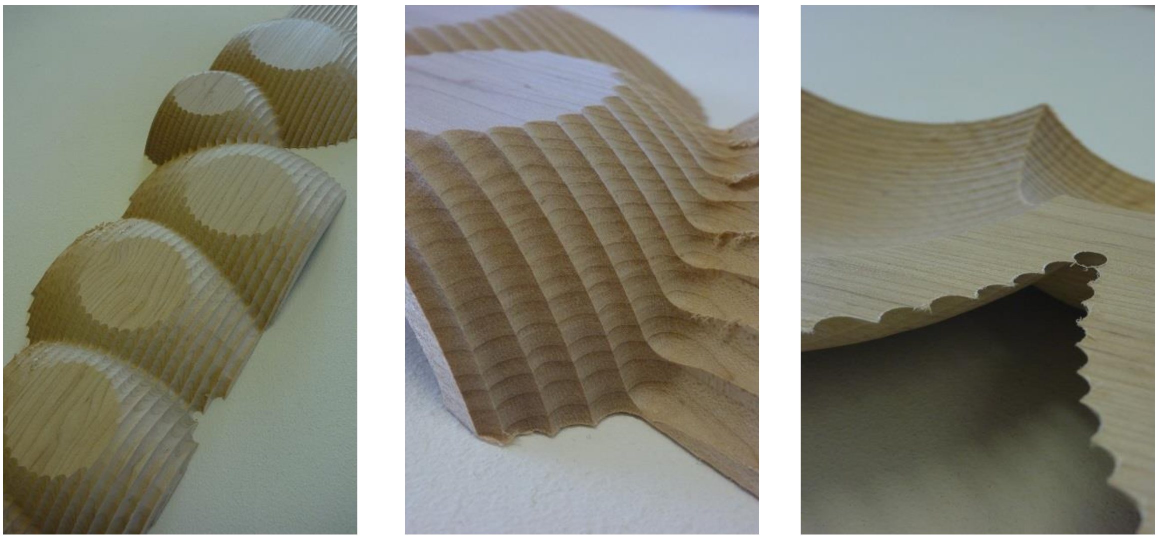


Figure 10: multi-spherical bowl

(figure 10)

The 6mm stepover produced deep scallops, suggestive of traces of making left by craft wood carvers. The marks echoed those left by the cutting of a chisel, and were particularly reminiscent of the finish David Pye's fluting engine left on the surface of his bowls.

[5] Reeded glass is a traditional textured flat glass available from companies such as Pilkington http://www.pilkington.com/en-gb/uk/products/product-categories/decoration. It has a ribbed/fluted surface that distorts the light, obscuring the view for purposes of decoration or privacy.

The definition of the scallops was crisp with minimal grain tearing, and a distinct line between the cuts defined the form of the surface and highlighted the grain and material qualities of the wood. However, the deep scallop resulted in sharp edges and spikes being left on the external rim of the bowl. These were not only prone to splintering but also made safe handling of the work problematic, so even though the scalloping depth was visually successful, the use of shallower scalloping on external surfaces was deemed to be more appropriate to an object that would be handled, especially where cuts ended at acutely angled edges.

As with the results of the internal cutting tests, a further unexpected visual effect was observed with the external cutting tests. At the point the router cutter transitioned from a surface sloping in one direction, across to a surface sloping in an opposite direction, the cutting head appears to move sideways, although it is actually moving in a straight line. This visual illusion was due to the fact that although the centre line of the tool doesn't move, when the tool is cutting surfaces that angle down left to right it cuts mainly to the left of the centre line, and when cutting surfaces that angle right to left it cuts mainly to the right of the centre line (figure 11). This gives the illusion that the cutter is travelling side to side, and the larger the cutter and the steeper the angle, the more pronounced the

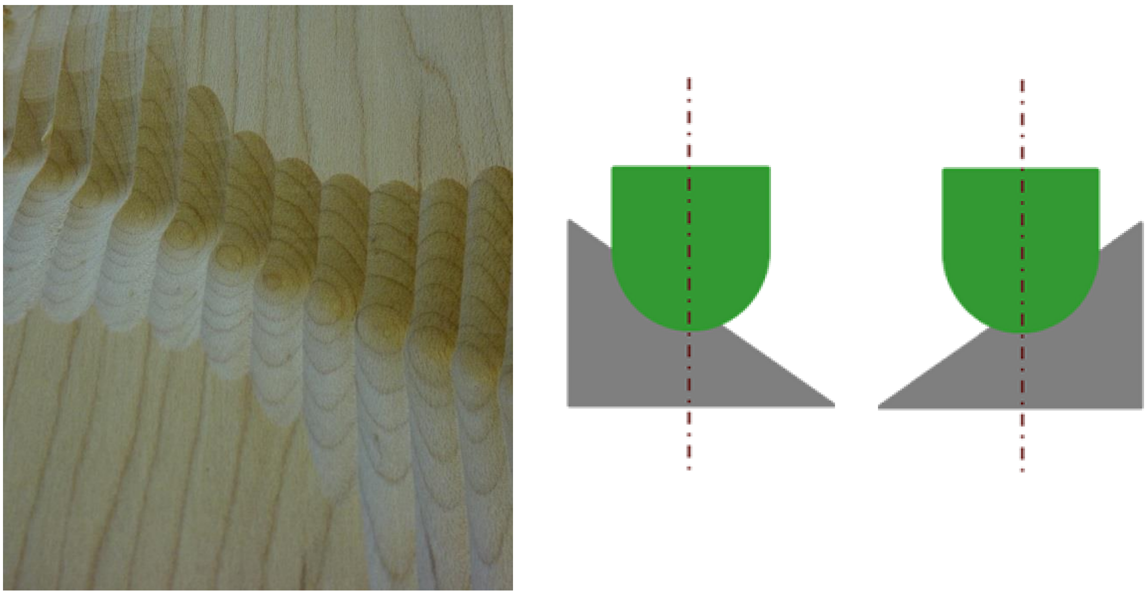


Figure 11: visual illusion of sideways cutter head movement

illusion.

This again highlighted the need for careful observation of results to deepen material and process knowledge, and inform a more engaged approach to the physical process of digital making. By understanding the relationship of machine set-up to physical results, one can develop a more empathetic approach, utilising the subtle and often unnoticed qualities of machine making in the development of more materially sensitive and expressive surfaces and forms.

5. Application of test results within an exhibition piece

An invitation to exhibit a piece of work was taken as an opportunity to consolidate and embed the results of the research testing thus far, within a more finalised piece. The work was to embody and highlight the qualities revealed in the testing period, using deeper scalloped cuts for internal bowls to create a bold chiselled surface, and contrasting this with shallower scallops for the external cuts, giving a subtle visual and tactile surface finish.

To highlight these qualities, a multi-elliptical bowl form was developed, with the carved bowl forms overlapping the edges of material (figure 12). This use of ellipses combined with a square edged framing device, had a number of aesthetic and manufacturing advantages:

- timber is normally supplied as long, narrow planks, and elliptical forms are more sympathetic to producing longer thinner forms than the earlier linked circles
- the length and width of ellipses can be changed independently of each other, making them a more flexible than circles when developing interlocking multi-bowl forms
- squaring the sides reduced the number of acute external edges, reducing the potential for splintering
- the squared sides also harmonised with the square ends that would be left after removal of the end lugs, enabling a manufacturing necessity to be aesthetically

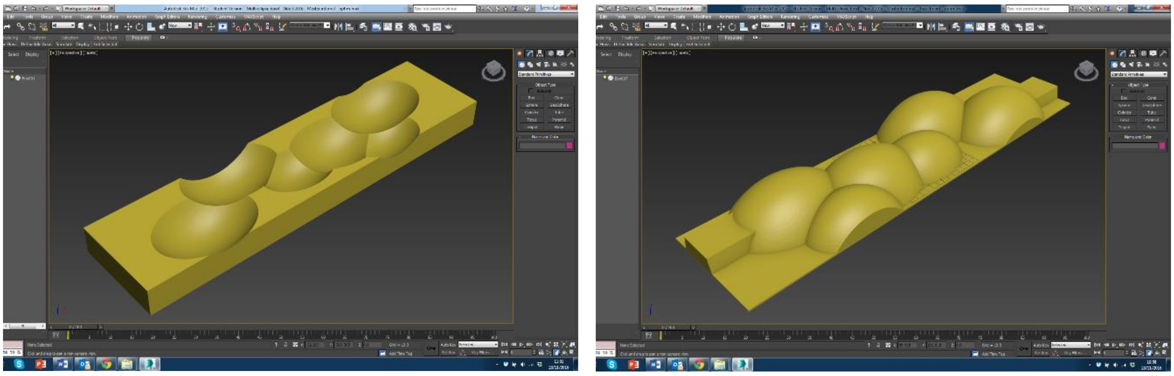


Figure 12: CAD model for linked elliptical bowl: internal and external cut models

integrated within the overall form and character of the piece

Oak was chosen as a hardwood with light colour and noticeable grain that would highlight the effect of the scalloping and surface textures, but also, as a quintessential British wood, would connect the work with the traditions of English hand carving.

Rough cutting was made with a 10mm square-ended tool, with a 10mm rounded-cutter used for the finishing cuts. Internal stepover was set at 6mm, and external stepover 3mm. Overall, the cutting was relatively fast, with the rough cutting taking under 1hr 30mins per side, and finishing cuts taking just 7 minutes (figure 13). After the end lugs had been removed, the piece required only very light

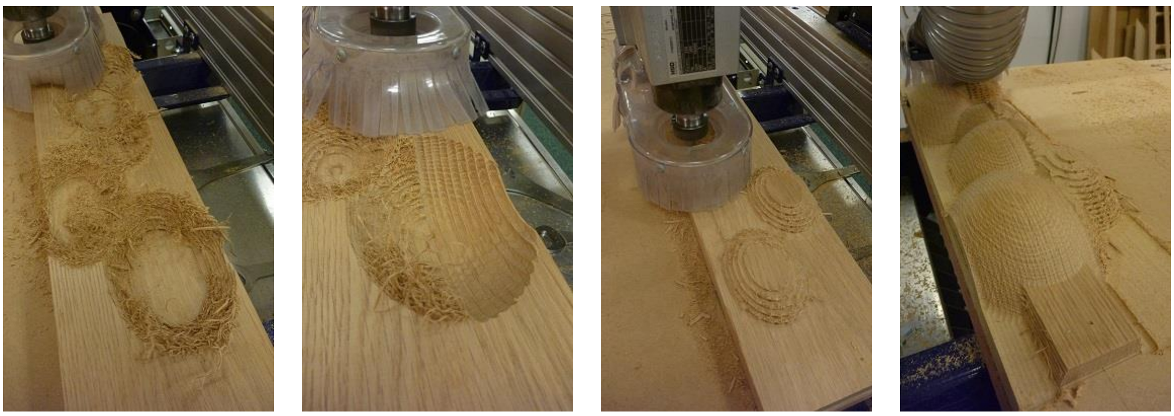


Figure 13: rough and finishing cutting of linked elliptical bowl

finishing to remove some minimal tearing, and a light coat of linseed oil to seal the work.

6. Conclusions

The finished piece (figure 14 & 15) embodies the material and surface qualities observed and developed in the research testing. The scalloped textural surface of the work is reminiscent of the chiselled marks left by the hand carving of wood and the fluted surfaces that were characteristic of

Figure 14: Linked Elliptical Bowl – David Grimshaw 2016

the work of David Pye, who has been a significant inspiration for the research.

The deeper scalloping of the internal surfaces highlights the grain figure of the oak, contrasting with the subtle tactile quality of the shallower scalloping of the external surface. The smooth surface geometry of the CAD model has been transformed into expressive textural surfaces, generated only by the control and set-up of the physical parameters of the digital cutting process. Further adjustments to cutter size and stepover will enable new and unique versions to be generated from the same model, each with its own subtle variation of surface character, finish and texture.

The work embodies an expressive materiality reminiscent of hand making, allied to an accuracy of execution achieved by the precision cutting of the digital router. As such, the piece is ambiguous, a hybridisation of hand and digital with expressive surface qualities in tension with an unfamiliar linearity of cut that hints at its digitally designed and manufactured origins.

This developing research points to a more expressive, nuanced and materially sensitive use of digital technology, harnessed in the creation of work that connects future digital manufacturing with the material knowledge and sensitivities embedded within the long history of craft and hand making.

Figure 15: Linked Elliptical Bowl – David Grimshaw 2016 (details)

The research also encourages continued support for the delivery and acquisition of material and process knowledge within contemporary design education, and highlights the importance of retaining and promoting traditional craft and material making practices within design teaching and learning. It demonstrates how embedding material making knowledge and applying this within digital design and manufacturing, can produce work that is more materially sensitive than might be achieved by using purely digital design methodologies, and promotes the value in engaging with the material opportunities inherent within physical making processes.

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About the Authors:

David Grimshaw is Programme Leader for MA/MSc Product Design at Manchester School of Art, and was previously a furniture design consultant. The craft and materiality of furniture design underpins his research into developing materially sensitive approaches to digital manufacture and making.

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